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EXPLOSIVES RESEARCH COMMITTEE (PHYSICS AND PHYSICAL CHEMISTRY)

Studies of shaped charges by flash radiography.

II. The Munroe Effect.

A joint report
by J. L. Tuck (M.D.1) and Armament Research Dept., (Radiological Section).

Communicated by the Director, M.D.1

June, 1943.
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SUMMARY.

Radiographs are presented showing stages in the development of the Munroe effect in an 80° cone and a spherical cap, and the projection of some plane discs.

A time scale has been recorded on the radiographs by the use of a detonating fuse clock.

In the case of the 80° cone, the formation of jet and plug can be followed from the incidence of the detonation wave, up to about 60 microseconds later, when the jet is some 30 cms. long. The jet from the spherical cap can be followed for 15 cms.

Measurements from the radiographs have yielded velocities for the jet and plug from the 80° cone, and for the projected material from the plane discs. Evidence of the degree of fragmentation both in the curved and flat linings is obtained. The information that these radiographs yield about the formation and nature of Munroe jets is discussed.

It is concluded that for the 80° cone, the results are in good agreement with the hydrodynamic theory of the Munroe Effect (i, ii).

INTRODUCTION.

The technique of these experiments was given in the previous paper. The method briefly is to use an intense flash of X-rays, lasting some fraction of a microsecond, to record a shadow of the rapidly changing configuration of a shaped charge during and after detonation. The metal parts throw clear shadows, uncomplicated by flash and smoke.

The signal for the production of the X-ray flash, has to be given in advance of the instant it is desired to record. The signals, in correct sequence, in the very small time intervals required, are given by the passage of a detonating wave down a measured length of detonating fuse.

i. A.C. 3596 - J. L. Tuck - A note on the theory of the Munroe Effect.
ii. A.C. 3734 - G. I. Taylor - A formulation of Mr. Tuck's conception of Munroe jets.

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Previous experience had shown that the delay associated with the X-ray-tube firing circuits was not constant, so an independent time measurement was obtained from a clock consisting of a length of detonating fuse which was simultaneously radiographed by the flash. Wire indices on the cordtex clock, which can be seen along the edge of some of the reproduced prints, formed reference points, by which the progress of the detonation wave could be measured.

The exact point of the detonation wave front was made more distinct by painting the cordtex with a thin lead oxide suspension.

A steel wire, held radially in the plane of the base, with its end touching the outside of the charge, was at first used to indicate the starting position of the lining. It can be seen in Shots A.1, A.4, etc.

In spite of some damage by the blast, it served for this purpose, until the better method was evolved, of taking a preliminary weak exposure before firing, through an intensity reducing screen. Such ghosts are to be seen on Shots A.3, A.12, etc., and they form a very satisfactory method of working. In order to prevent possible confusion in the interpretation, all shots having a ghost exposure have a suffix (G) as their index number.

Description of the Charges.

All the charges were 30 m.m. diameter, and contained 30 gms. of Plastic RDX(PE), in a cardboard tubular case of wall thickness 1.5 m.m.

It has not been possible to fire other than very lightly encased charges, on account of the difficulty of protecting the X-ray tube and photographic film from the fragments.

80° Cones.

Material	...	Brass.
Diameter	...	30 m.m.
Thickness	...	.024" = 0.64 m.m.

If the Munroe effect be defined and measured in terms of the development of penetrating performance, then the proportions of this charge were chosen to give around the maximum Munroe effect for such a lightly cased charge. For example, one of the charges, fired against a massive mild steel target, at a distance of 1½ diameters, gave a penetration of 81 m.m.

Spherical Caps.

Material	...	Cadmium.
Diameter	...	30 m.m.
Thickness	...	.056" = 1.4 m.m.
Curvature	...	22 m.m. radius = .75 D.

The proportions of these charges were chosen from the papers of workers (iii), who have studied charges of this shape.

iii. A.C.2461 - Evans & Ubbelohde - The Munroe jets formed by various lined hollow charges.

Plane Discs.

The thickness of the discs was selected to be comparable with that of the 80° cone lining, with the intention of deriving from the radiographs, information concerning the magnitude of the velocity of projection of the lining material, and more particularly, how this velocity varied across the face of the charge.

Observations on the 80° Cone Pictures.

The collapse of the cone is seen to take place progressively from apex to base, with the development of an axial jet and plug.

The velocities obtained for the jet and plug, have been measured from the radiographs, and plotted in Fig. 1. The values are:-

$$V_j = 4.25 \times 10^5 \text{ cm./sec.} = 14{,}000 \text{ f.s.}$$

$$V_p = 0.715 \times 10^5 \text{ cm./sec.} = 2{,}350 \text{ f.s.}$$

This behaviour is in accordance with that expected on hydrodynamic grounds if the conical lining were behaving as a fluid shell. That such behaviour can be justified, without melting of the metal, is on account of the smallness of the rigidity forces of the metal, when compared with the forces exerted by the explosive, and arising dynamically out of the subsequent high velocity flow.

The treatment (2) for a fluid shell whose thickness is inversely proportional to its distance from the axis gives expressions for the plug and jet velocities Vp and Vj of

$$V_j = \bar{V} \cot \alpha/2$$

$$V_p = \bar{V} \tan \alpha/2$$

where $\bar{V}$ = velocity of initial projection of lining.

$\alpha = \theta + \varepsilon$

θ = semi-angle of cone.

ε = throw-off angle of the projected material.

whence $\bar{V} = (V_p V_j)^{\frac{1}{2}}$

and $\alpha = 2 \tan^{-1} V_p/V_j$

Using the experimentally observed values of Vp and Vj

we find $\bar{V} = 1.73 \times 10^5$ cm./sec. = 5,700 f.s.

and $\alpha = 44.5^\circ$

This value of $\bar{V}$ for cone material of thickness - (.024") may be compared with the observed maximum velocities of projected plane discs of 7,600 f.s. for .03" and 11,300 f.s. for .02" thickness respectively (Fig.1 and plate 3).

The calculated value of yields for the throw-off angle

$$\varepsilon = 4.5^\circ$$

We can obtain an independent observation of by combining the value of $\overline{V}$ obtained above with the detonation velocity Vd in the equation

$$\frac{\overline{V}}{VD} = \frac{\sin \varepsilon}{\cos \varphi}$$

giving $\alpha = 9.5^{\circ}$

which is about twice the previous value.

This inconsistency seems to be reconcileable very satisfactorily as follows: in deriving the equation yielding the first value of from Vp and Vj, G. I. Taylor makes the reasonable approximation that the motion of points in the projected front of lining material is normal to that front. Actually, the direction of motion of such points makes an angle to the normal which, in the case of a wave moving parallel to the surface, amounts to $\alpha/2$ as he showed in his paper on the detonation of a long cylindrical bomb (iv). But further discussion on this point may be left to another paper.

A striking feature of the radiographs is the appearance of a frill or rim, which forms about the plane of the base of the cone. This rim appears to be formed from the regions of the cone near to the edge, and to have a velocity gradient which changes its shape from the original cone, through a curved brim, and an inverted cone, to a cloud of fragments moving with a velocity of a few hundred feet per second. Sometimes a ring is observed (A.4, A.9). There is no doubt that this phenomenon is due to the fall in $\overline{V}$, the intial projection velocity of the cone material at the edges of the charge.

Some such effect would be expected in heavily confined charges, merely on account of there being less explosive behind the cone towards the edge, and in lightly confined charges, such as had to be used in these experiments, the effect is accentuated.

The residual ring (A.4, A.9) which sometimes appears, is doubtless due to the entrapping of a ring of air about the extreme edge of the cone lining during assembly of the charge. This rim would then be left behind by the faster moving main body of the cone lining.

There is no evidence on the radiographs of fragmentation of the lining during collapse.

The view that fragmentation of the lining takes place at or during projection from the explosive, does not fit in very satisfactorily with the hydrodynamic theory of the Munroe effect.

So far as the outside layers of the lining are concerned, the plugs recovered after firing Munroe charges having brass or steel linings and developing armour penetration of the highest standards, show the original outside surface markings of the cone lining with such fidelity, that the hypotheses that such material had undergone fragmentation and then reunited is quite untenable.

As for Hopkinson fragmentation from the inner surface of the cone, the minimum requirement for the hydrodynamical mechanism to apply, is that no tangential flow takes place along a circle about the axis of the charge. If the fragmentation is so fine that no gaps exist

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iv. PHYS/EX.100 - G.I.Taylor - The detonation of a long cylindrical TNT bomb.

between the particles, into which flow could take place, then hydrodynamically speaking, the system can be treated as a fluid and the hydrodynamical mechanism can be applied.

It is difficult from the radiographs, to give a precise instant for the completion of the formation of jet and plug. The jet continues to elongate up to the limit of the time of observation but the issuing jet seems to be thinning at 30 microseconds (A.10) and an abnormal graininess can be discerned in the jet on the negative at 35 microseconds (A.11).

Thereafter, a pronounced structure appears in the jet. The structure appears distinctly regular, with a period of about 1 cm.

Spot microphotometer readings made at intervals of 1 m.m. on the jet image, have not provided, however, any very convincing evidence of periodicity.

The explanation of the indefiniteness in the point of separation of jet and plug, is to be found in the decline in $\bar{V}$ from axis of cone lining to the edge. This would have the effect of smearing out the well defined separation that would be expected with a uniform value of $\bar{V}$ and also would be expected to produce a jet with a velocity falling from tip to tail.

It is tempting to explain the break-up of the jet in terms of a tension arising out of this velocity gradient. But there seems no evidence that the jet is a continuous rod capable of supporting a tension and the indications are rather the reverse since a graininess is already visible at A.11 before the main break-up has developed, and a general impression of cloudiness is given even earlier.

<u>The spherical cap lining.</u>

The radiographs obtained show the performance of this lining to be consistent, judging from the similar appearance of some of the pictures.

Measurements of the velocities from the radiographs give rather variable values for the jet velocity in the region of 10,000 f.s. This value seems low compared with the results obtained elsewhere. A possible reason for this may be that the convergence of these caps being low, may result in the formation of the jet being incomplete during the period covered by the radiographs.

From the point of view of the hydrodynamic theory of the Munroe jet, the sequence of events in the formation of a jet from a spherical shell is obscure.

The general similarity in the behaviour of spherical caps and cones and indeed of all re-entrant shapes, could be held to be evidence that a mechanism which accounts with some completeness for the behaviour of the conical lining, would play a part in the mechanism of all the other re-entrant shapes. In the case of a spherical shell, the presentation of the collapse as the continuous operation of a simple process, as can be done for a cone, is not possible. Treating the spherical cap in a manner similar to that of a cone, the detonation wave encounters first a flat surface. As the successive cones of the sphere are exposed to the pressure behind the advancing detonation wave front, they could be regarded as successive frustums of a cone of constantly decreasing angle.

Unfortunately, the theory predicts that the later cones, having a smaller angle of convergence, should develop a thinner and faster jet. Whether this faster but later material has to pass through the earlier but slower material, or whether it in fact precedes it cannot be answered from the pictures.

The flat discs.

The curvature of the front of projected disc material can be shown to be a consequence in part of the curvature of the incident detonation wave, which projects the centre of the disc before the edge, and also of the fall in projected velocity toward the edges. This latter effect is responsible for the increase in curvature of the projected material front, with time.

The degree to which the projected material holds together without breaking into fragments is noteworthy and provides additional evidence of the unlikelihood of the fragmentation of Munroe linings prior to collapse.

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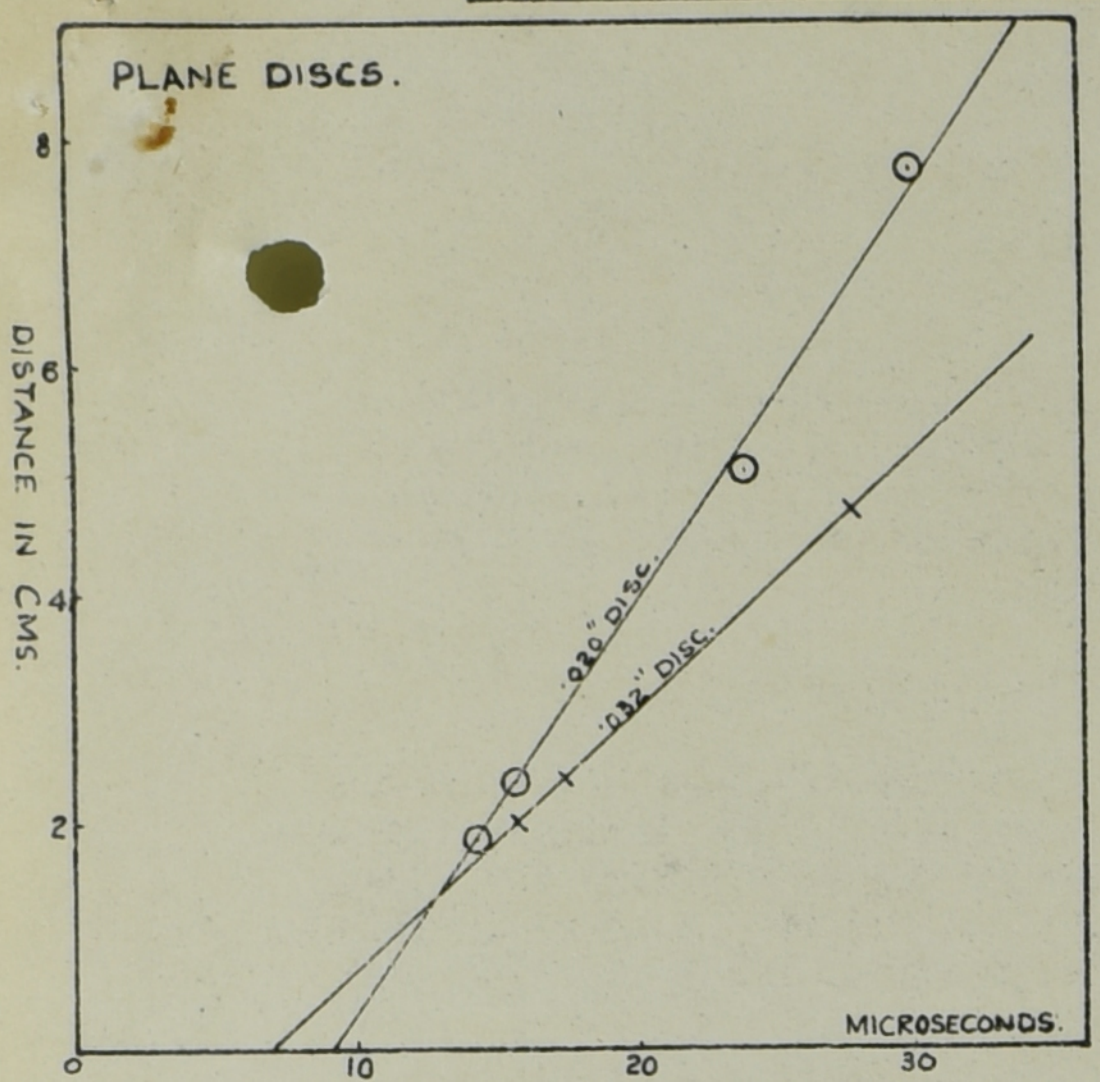
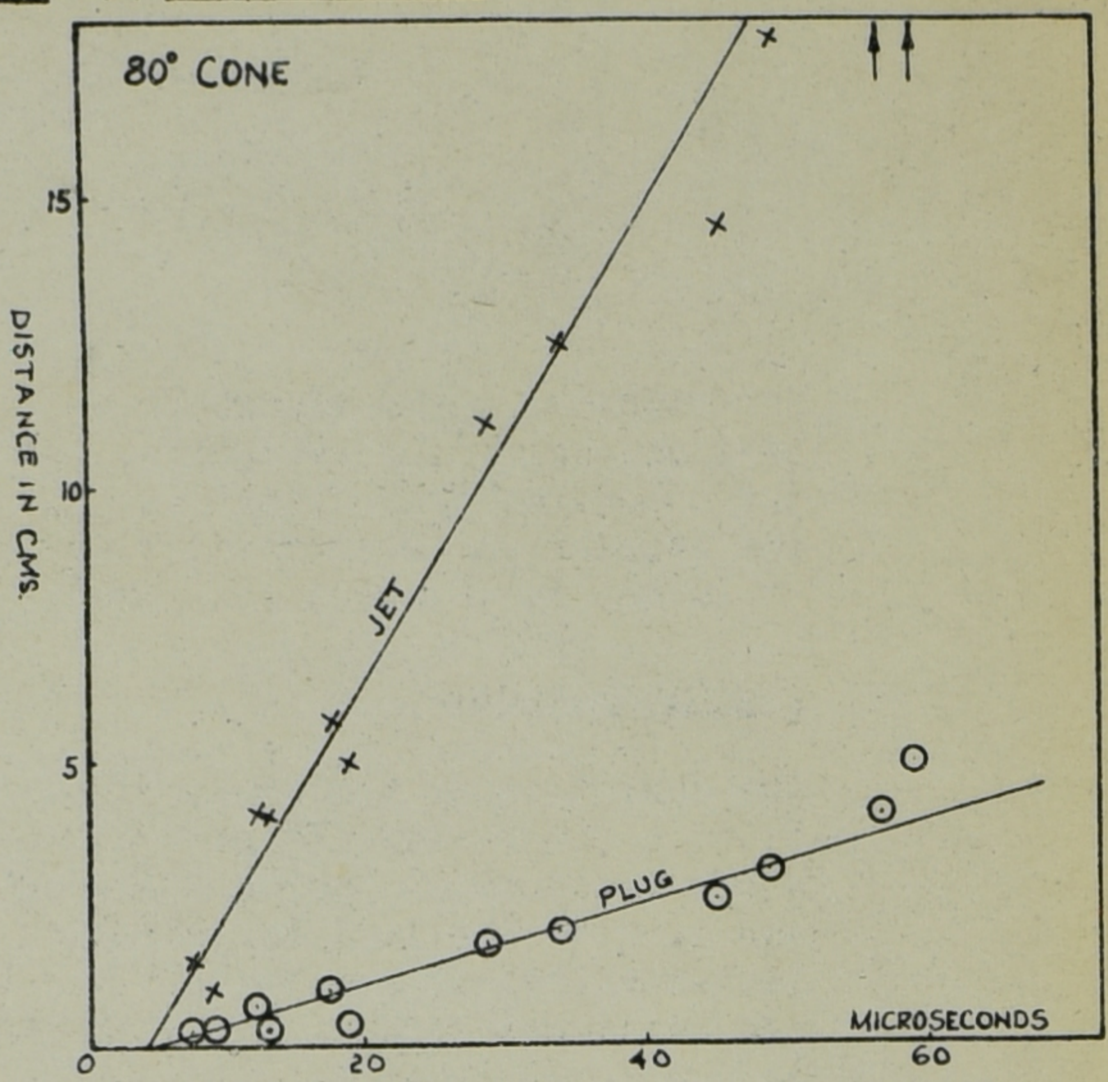
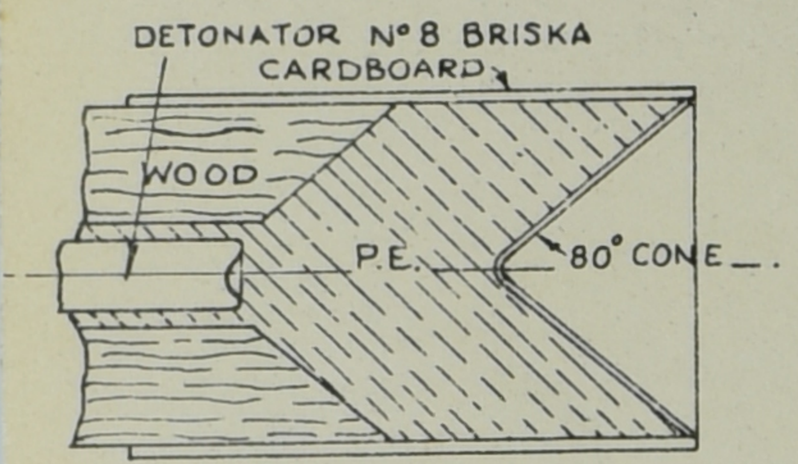
MUNROE EFFECT 80° CONE (a) EXPERIMENTAL.





DISPLACEMENTS MEASURED FROM THE RADIOGRAPHS AND PLOTTED AGAINST TIME.



INTERPRETATION FROM THE RADIOGRAPHS OF THE STAGES IN THE COLLAPSE OF AN 80° CONE.

THE CURVED RIM WHICH FORMS ROUND THE PLUG CAN BE SHOWN TO BE A CONSEQUENCE OF THE FALL IN $\overline{V}$, THE INITIAL PROJECTION VELOCITY OF THE CONE LINING FROM AXIS TO EDGE

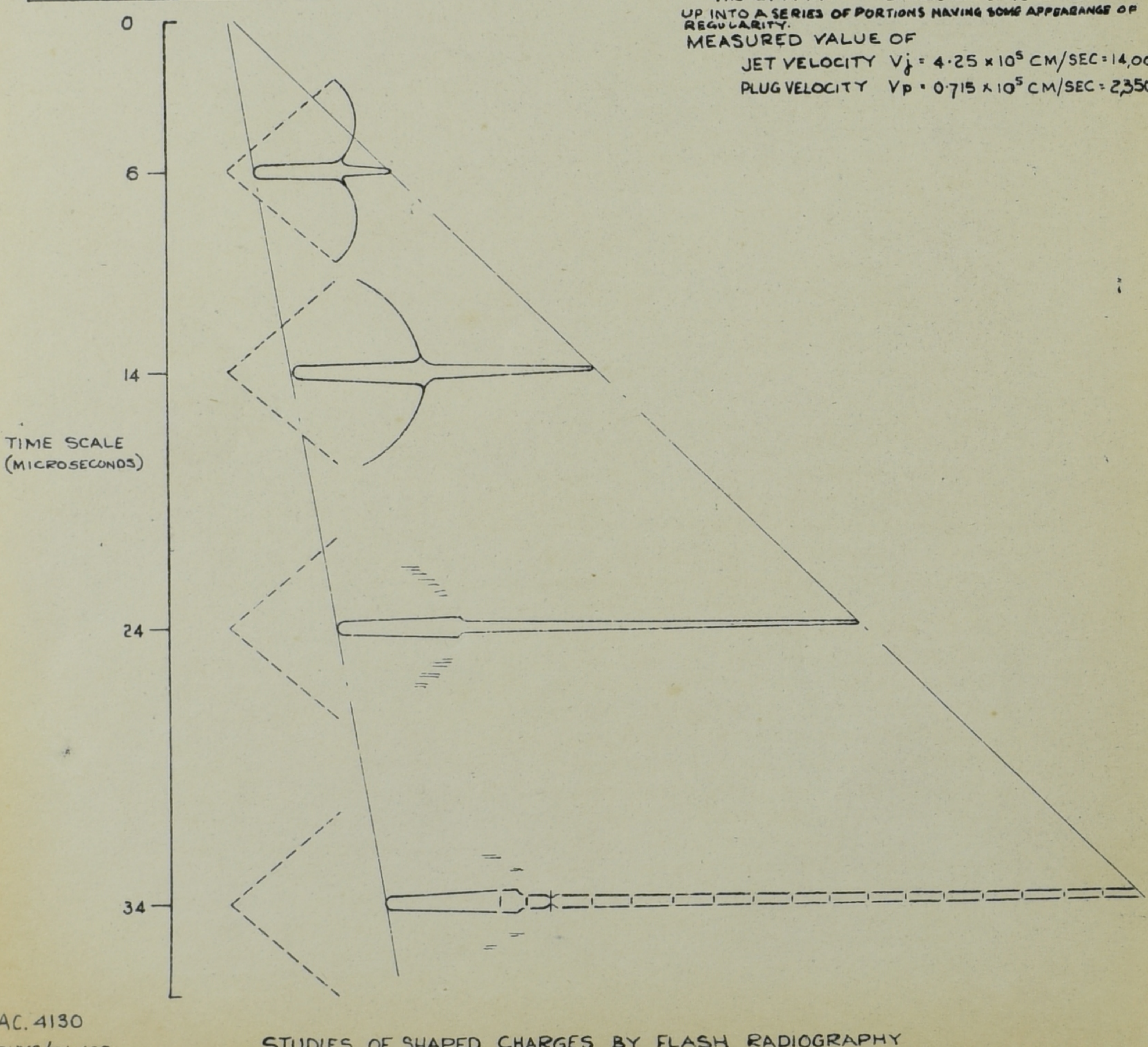
THIS FALL IN $\overline{V}$ IS LIKEWISE RESPONSIBLE FOR A VELOCITY GRADIENT IN THE JET WHICH TENDS TO STRETCH IT AND TO MASK THE DEFINITE SEPARATION WHICH APPEARS IN THE IDEAL MODEL OF FIG 2.

THE JET IN THE LATE STAGES APPEARS TO HAVE BROKEN UP INTO A SERIES OF PORTIONS HAVING SOME APPEARANCE OF REGULARITY.

MEASURED VALUE OF

JET VELOCITY $V_j = 4{\cdot}25 \times 10^5$ CM/SEC = 14,000 F.S.

PLUG VELOCITY $V_P = 0{\cdot}715 \times 10^5$ CM/SEC = 2,350 F.S.



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STUDIES OF SHAPED CHARGES BY FLASH RADIOGRAPHY

SK. 12849.

FIG. 2.

MUNROE EFFECT 80° CONE (b) THEORETICAL.

THE DIAGRAMS DEPICT THE COLLAPSE OF AN 80° CONE ACCORDING TO THE THEORY OF THE MUNROE EFFECT DEVELOPED IN PAPERS AC3596 AND AC3734

THE IDEAL CASE IS REPRESENTED WHERE THE INITIAL VELOCITY OF THE CONE LINING $\bar{V}$ IS EVERYWHERE UNIFORM AND THE THICKNESS OF THE CONE LINING VARIES INVERSELY AS ITS DISTANCE FROM THE AXIS OF THE CONE.

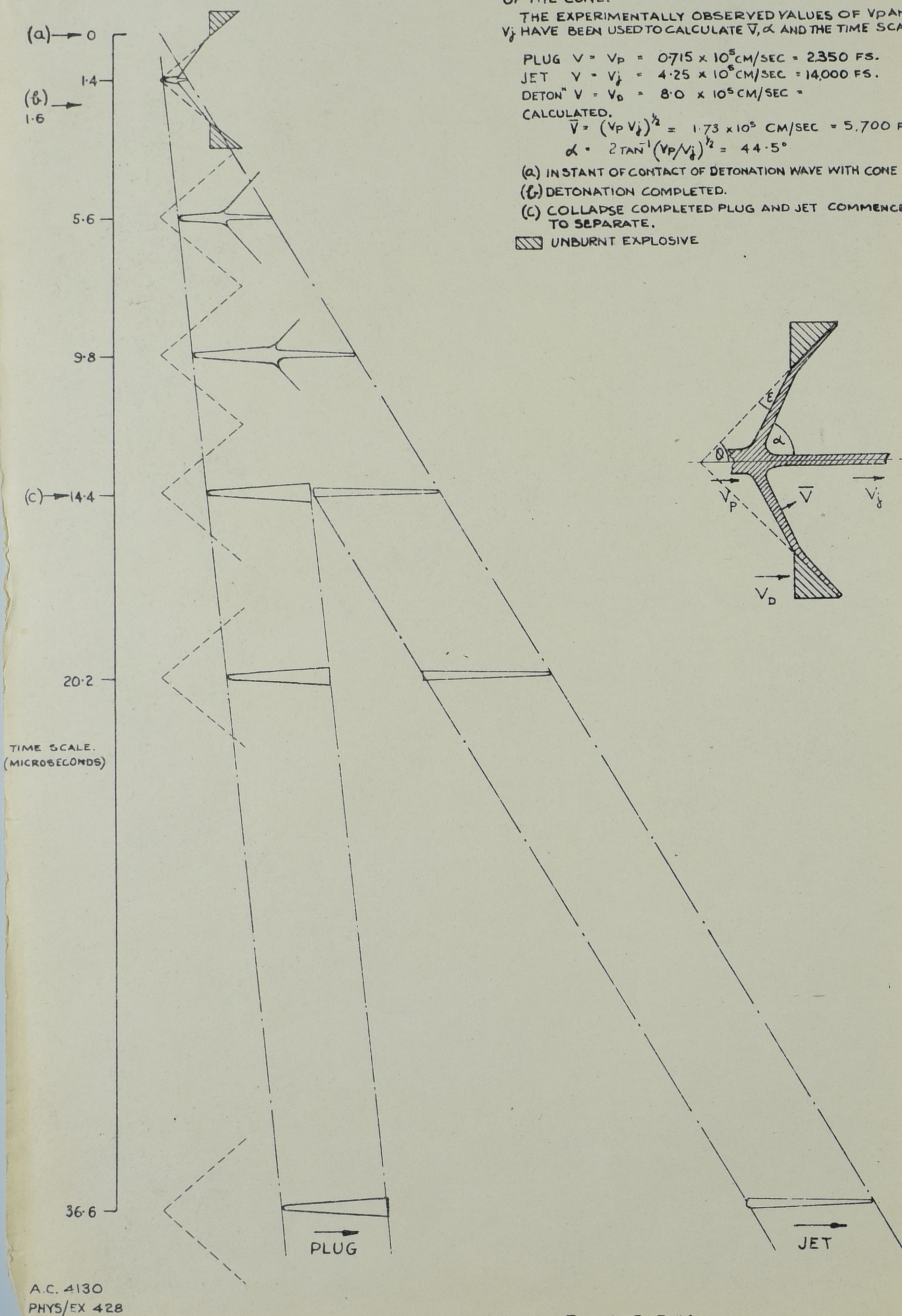
THE EXPERIMENTALLY OBSERVED VALUES OF V_P AND V_j HAVE BEEN USED TO CALCULATE $\bar{V}$, α AND THE TIME SCALE

PLUG $V = V_P = 0{\cdot}715 \times 10^5$ CM/SEC = 2,350 FS.
JET $V = V_j = 4{\cdot}25 \times 10^5$ CM/SEC = 14,000 FS.
DETON^n $V = V_D = 8{\cdot}0 \times 10^5$ CM/SEC =

CALCULATED.

$$\bar{V} = (V_P V_j)^{1/2} = 1{\cdot}73 \times 10^5 \text{ CM/SEC} = 5{,}700 \text{ FS.}$$
$$\alpha = 2\tan^{-1}(V_P/V_j)^{1/2} = 44{\cdot}5°$$

(a) INSTANT OF CONTACT OF DETONATION WAVE WITH CONE
(b) DETONATION COMPLETED.
(c) COLLAPSE COMPLETED PLUG AND JET COMMENCE TO SEPARATE.
▨ UNBURNT EXPLOSIVE



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STUDIES OF SHAPED CHARGES BY FLASH RADIOGRAPHY.

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